

Theory and methodology for high-performance material-extrusion additive manufacturing under the guidance of force-flow

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Abstract

Anisotropy on strength between different layers and filaments in the material extrusion (MEX) process has a significant influence on mechanical performances of fabricated objects. A novel theory and methodology is proposed to improve mechanical performances of parts by designing and controlling the anisotropy. Anisotropy can then be in alignment with load paths under the guidance of force-flow. In this study, by (1) dividing the part into several building areas and generating corresponding building direction considering the force-flow properties of the part; (2) generating novel toolpaths which are based on principal stress lines (PSL) and will map the direction and magnitude of PSL, the adverse influence of anisotropy on mechanical performances between different layers and filaments can be minimized respectively. A 6-axis robot arm integrated with an extrusion system is constructed to handle the multi-direction building of each building area. The study will advance the development of additive manufacturing from "prototype" to "end-use".

Keywords: Additive Manufacturing; Material Extrusion; Mechanical Performance; Anisotropy; Force-Flow

Introduction

With the development of additive manufacturing (AM) from “prototypes” to “end-use”, its focus has advanced from “geometry” to “performance”, e.g. the fuel pump nozzles for the LEAP engine produced by GE using 3D printing [1]. The process of material extrusion (MEX), generically known as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF), in which the part is built up with fused filament from line to face and then to body(1D→2D→3D), causes the poor tensile and shear strength between different filaments and layers. Using anisotropy, the fabricated part shows different strength performance in different directions and significant adverse influence on the mechanical performance of the part. For traditional MEX process, the mechanical performance of the part in building direction (z-direction) can be about 50% weaker than in the printed plane (x-y plane) [2]; but the strength of the part which is printed with optimized toolpath according to its stress condition, can increase by about 45% [3], and the strength of the part only can reach about 25-50% of the part’s material [2]. There are several ways to decrease anisotropy and improve mechanical performance using a special process design, for example, the z-pinning approach for depositing continuous material across successive layers [2], reducing anisotropy via ionizing radiation [4]; increasing isotropy by alternate orientation of continuous filaments in the part [5]; or even using new materials with superior properties, such as using continuous fiber-reinforced materials in FDM [6,7]. But all these approaches can’t fundamentally

solve the adverse effect of anisotropy brought by the MEX process inherently. In contrast to reducing anisotropy (treating it as a disadvantage), taking full advantage of anisotropy is very commonly seen in the natural world (e.g. skeleton growth, plant fiber). If the anisotropy of a part can be matched with the load condition (e.g. the growth of plant fibers or skeleton is consistent with the direction of stress), this anisotropy may become a relative advantage, which can greatly enhance the mechanical performance of additively manufactured part.

In this paper, a novel theory and methodology of MEX process is proposed to minimize the adverse influence of anisotropy on mechanical performance, by designing and controlling anisotropy aligning with load paths under the guidance of force-flow, thus to improve the mechanical performance of the part and realize the customization of both “geometry” and “performance” of fabricated objects.

Literature Review

In the MEX process, building direction (BD) has significant influence on the mechanical performance of a part due to the anisotropy between different layers. Meanwhile the construction of support, surface quality and building efficiency are also functions of BD. Currently, most work about the optimization of BD focus on the surface quality, accuracy, support, time and cost, but there is limited work about its influence on mechanical performance. Previous studies show that the performances, such as strength and ductility of a part built by the MEX process, largely depend on the direction of load, and the strength of the part in building direction (z-direction) can be about 50% weaker than in the printed plane (x-y plane) [2]. Weak links in different layers cause poor tensile and shear strength. The mechanical performance of part can be improved by optimizing the BD according to its force-flow (or load path [8], which can be visualized by principal stress lines [9]), such as making the BD perpendicular to the tensile stress[10]. In this way, C. Klahn et.al. [11] proposed to improve the mechanical performance of snap-fit joints by optimizing the BD. M. Taufik et.al. [12] made a review for the effect of BD strategies on several factors including surface quality, dimensional accuracy, support required, build time and part strength. A method of multi-direction slicing and building was proposed by Ding et.al. [13,14], including decomposition–regrouping, a method for multi-direction slicing (volume decomposition and sub-volume regrouping), the impact of different geometric features (e.g. holes) on multi-direction slicing strategy, as well as different toolpath patterns. However, this method doesn't take the stress condition (under a specific load condition) into consideration.

The position and orientation of the fused filament within layers greatly affect the mechanical performance of part. Toolpath patterns play an important role in performance [11,15]. The weak links in different filaments cause poor tensile strength in the direction that is perpendicular to the axis of the filament, which shows the anisotropy between different filaments (within the layer) [3,16]. The traditional toolpath is directional homogeneous which is mainly based on the geometric information of the part and efficiency, without consideration of the load condition. To deal with such problems, a depositing trajectory according to principal stress directions is used [16]. Considering the performance under different toolpath patterns, C.M.Al et.al. [3] found that the mechanical performance of the part built with toolpath which is designed along the direction of stress increase by about 45%. However, the design of the toolpath considering the mechanical performance of part (i.e. load-based infill [7]) has not been studied in depth, and the traditional 3-axis MEX process can only produce planar toolpath which only could be called as 2.5D printing strictly without 3D toolpath.

Increasing the degree of freedom (DOF) of movement has become a new way to overcome the disadvantage of the traditional 3-axis MEX process with only one BD. With the target of printing 3D models without support structures, Wu et.al. [17] presented a robotic system (a flexible building platform with a 6-axis robot arm, and a z-direction extruder) which includes the algorithm of decomposition and sequence planning. It was also mentioned that the collision between nozzle and the printed model cannot be resolved by changing the sequence of fabrication when the base cross-sections intersect with each other. I.Ishak et.al. [18] also achieved multi-direction 3D printing without support structures by using a robot-arm system. As for the printing of a part with large and complex volumes, a method for partitioning objects for 3D printing was proposed with several objectives being taken into consideration such as printability, assemble-ability and efficiency [19]. Tang et.al. [20] presented an algorithm of segmentation for dimensionally large objects taking the critical surfaces into account such as cylindrical and conic surfaces, and surfaces with high quality demand.

The fundamental cause of the poor mechanical performance of parts made in the MEX process is that the distribution of material (which causes the anisotropy) is not in alignment with the load condition. From the literature review above, it can be summarized that presently, work for the division of parts in AM are based on the consideration of geometry to increase the printability of complex parts instead of load condition to improve its mechanical performance. Generally speaking, the work for a comprehensive method is limited, in which multi-area building, multi-direction building and toolpaths could all be taken into consideration based on the load condition. This is what was proposed in this paper, which is believed can significantly minimize the adverse influence of anisotropy and finally improve the mechanical performance of additively manufactured parts.

The Proposed Methodology

The research framework in this paper is shown in Fig.1, and our proposed methodology includes three steps, as shown in Fig.2.

(1) Dividing building areas

The part is divided into several building areas based on both geometric features (planes, holes, ribs) and the force-flow properties of the part obtained by finite element analysis (FEA) under specific load condition. The corresponding BD for each building area is generated according to force-flow properties and the requirements of surface quality and building efficiency.

(2) Planning building sequence

The building sequence is planned with the targets at several factors including no collision between nozzle and the printed model, less or no support structure, high efficiency and less building time. It must be noted that the results of step (1) and (2) need to be optimized iteratively with the targets mentioned above.

(3) Slicing and generating toolpath

Each building area is sliced according to their own BD. Then, the corresponding toolpath of each building area is generated based on the principal stress lines (PSL), which is the mapping of the direction and magnitude of the PSL. It must be mentioned that the continuity of toolpaths should be maintained in some key features of stress concentration, such as holes.

In this paper, the proposed methodology is detailed by taking typical “L-shaped” bracket connectors part [8] as an example, which contains typical geometric features (e.g. planes, holes, ribs) and are widely used in aerospace industry with high requirement for strength (e.g. Airbus A320 hinge bracket produced with additive manufacturing technology [21]).

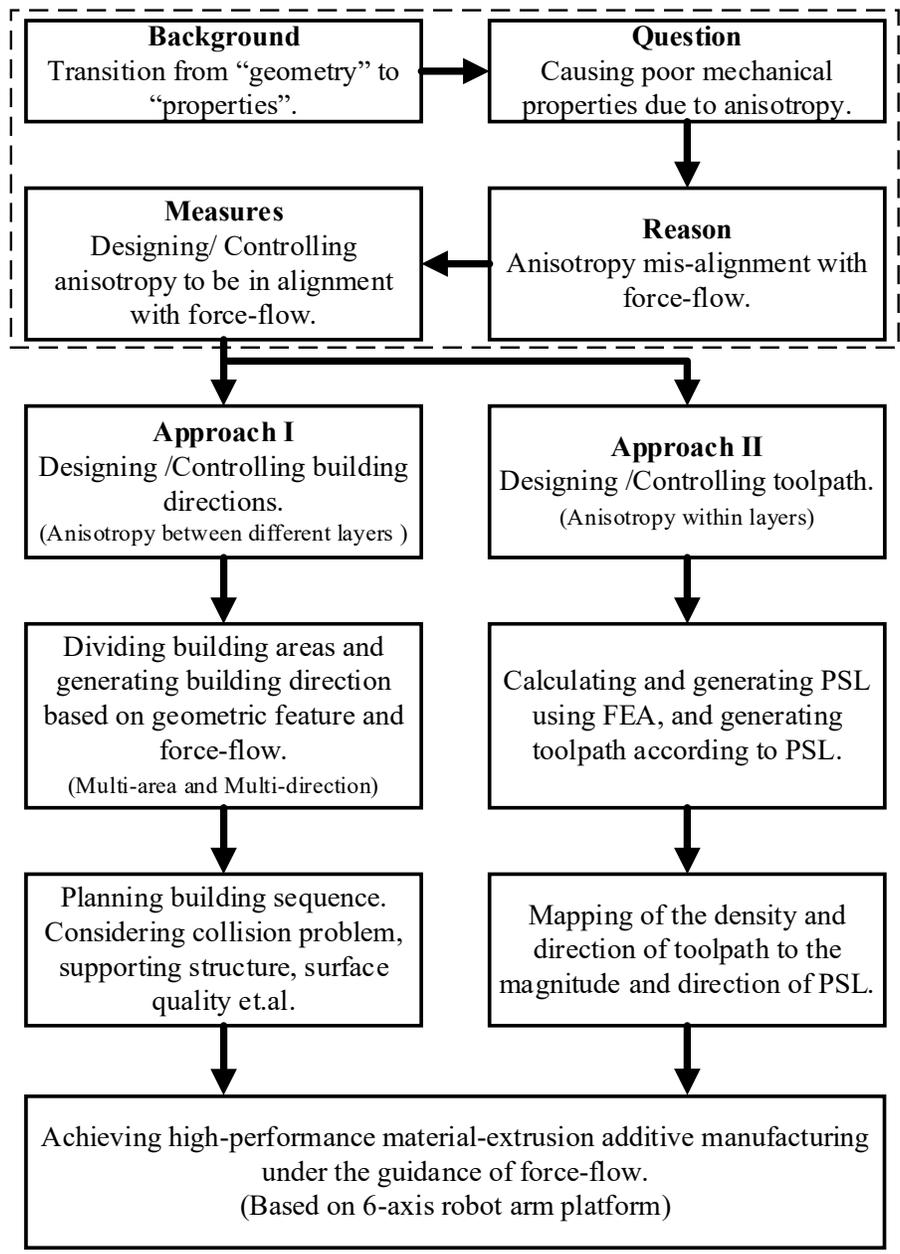


Fig.1 Research framework

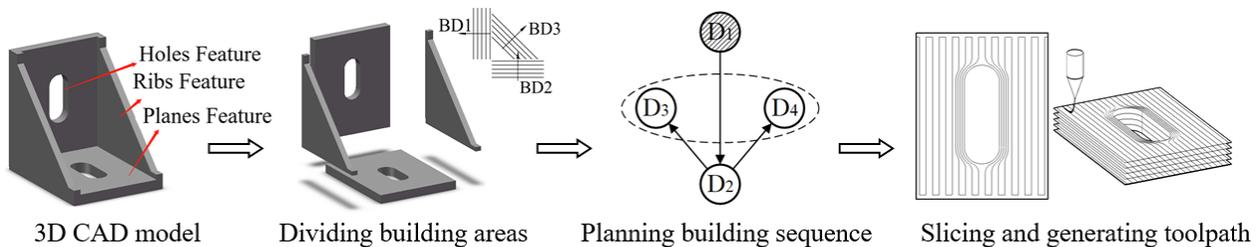


Fig.2 Steps for the proposed methodology

Dividing building areas

A three-level dividing strategy is adopted as shown in Fig.3.

(1) First dividing: The CAD model is divided using the geometric feature recognition technology according to the geometric features or additive manufacturing features of the bracket (i.e. planes, holes, ribs). As shown in Fig.3(I), the bracket is divided into three building areas.

(2) Second dividing: Based on the force-flow properties obtained by FEA under specific load condition of the bracket, the bracket is then divided on the basis of (1), following the principle that the overall force-flow direction in one single building area is consistent or roughly the same. Then the second divided parts will be recombined when needed. Because in most cases, the application conditions of the parts have been taken into account in the stage of geometric design, the dividing result of considering geometry is similar to or the same as that of considering force-flow (see Fig.3(II)).

(3) Third dividing: The bracket is then divided on the basis of (2), following the principle that the interfaces between building areas should avoid the stress concentration areas. In this step, the stress concentration areas will be separated out, and then be recombined with neighboring areas when needed. One possible result of third dividing is shown in Fig.3(III). To get better division, other factors such as the collision problem during the building process need to be taken into consideration.

After the dividing process, the BD for each building area will be generated following the principle that the BD should be perpendicular to the overall force-flow direction of the building area and to the corresponding surface. One possible division is shown in Fig.3(IV). And the slicing direction for each building area is correspondingly defined with the generation of BD. In this way, the adverse influence of anisotropy on strength between different layers will be minimized.

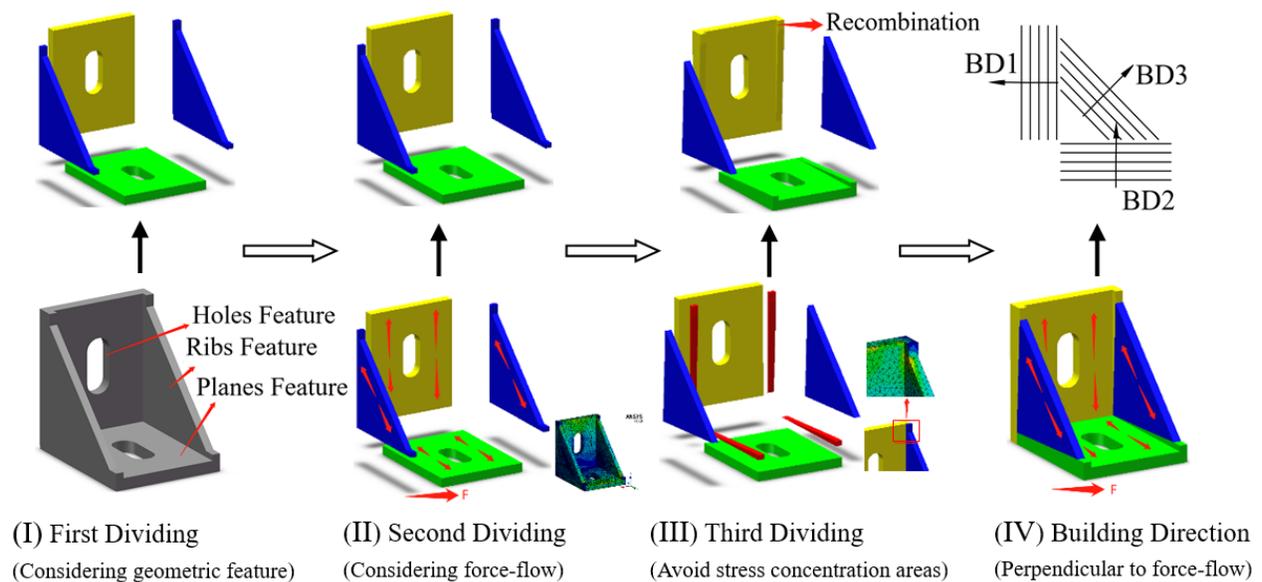


Fig.3 Steps for dividing building areas

Planning building sequence

The topological relations between different building areas are shown in an undirected graph. As shown in Fig.4, each node D_i in undirected graph G represents one building area, and each line represents the adjacency relations between D_i and D_j . After the initial node (the initial building area) is determined, the directed graph G^\wedge will be generated which represents the building sequence. In this way, the problem of planning building sequence of the building areas is converted to the problem of sequence for nodes connection in the directed graph. The sequence in the directed graph depends on the determination of the initial node, considering that the building of each step (except the first one) is on the basis of the parts which have already been built, and it should be optimized considering several factors, including no collision, less or no support structure, high efficiency and less building time.

As shown in Fig.4(III), 4(IV) and 4(V), node D_1 , D_2 , D_3 are used as the initial nodes correspondingly in the directed graphs. Fig.4(IV) is one possible sequence using node D_2 as the initial node. Actually, using node D_2 as the initial node, the possible building sequence is not unique which could be $2 \rightarrow 3/4 \rightarrow 1$ or $2 \rightarrow 1 \rightarrow 3/4$, as the node D_3 and D_4 are at the same priority level.

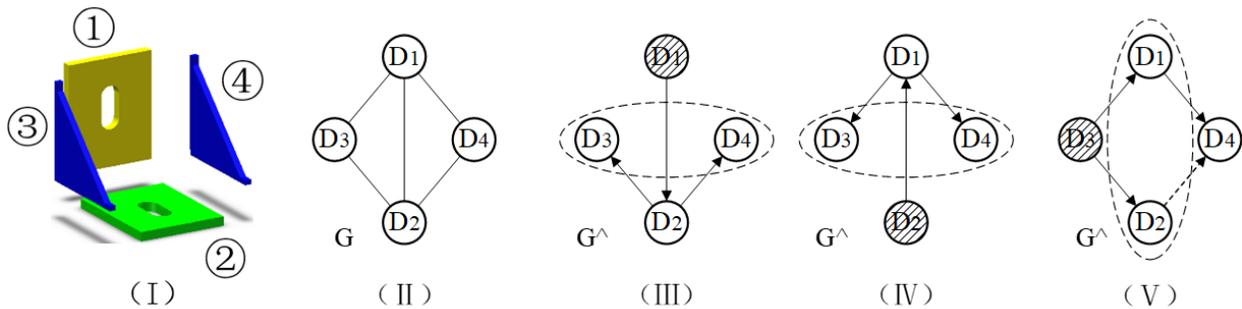


Fig.4 Building sequence representation using directed graph

Slicing and generating toolpath

Under given loads and boundary conditions, the PSL can be calculated using FEA, which is the visualization of load path. The toolpath is generated according to the PSL, which is optimized to make the tangent direction of each point on the toolpath to be consistent with the direction of principle stress. The variable density distribution of extrusive material is generated according to the magnitude of Von mises equivalent stress.

As for the planar building area in this example (bracket connector), considering that its dimension in thickness direction is much smaller than its length and width directions, the problem can be simplified as planar stress problems or thin plate bending problems, or the combination of both. According to the orthogonality of PSL (σ_I and σ_{II}) in the plane, the σ_I layers and the σ_{II} layers are alternately laid (see Fig.5). In addition, there is a positive correlation between the material distribution density and the magnitude of stress in the building area. For example, the toolpath should be denser in the areas of stress concentration than in other areas. In this way, the adverse influence of anisotropy on strength between different filaments (within the layer) will be minimized.

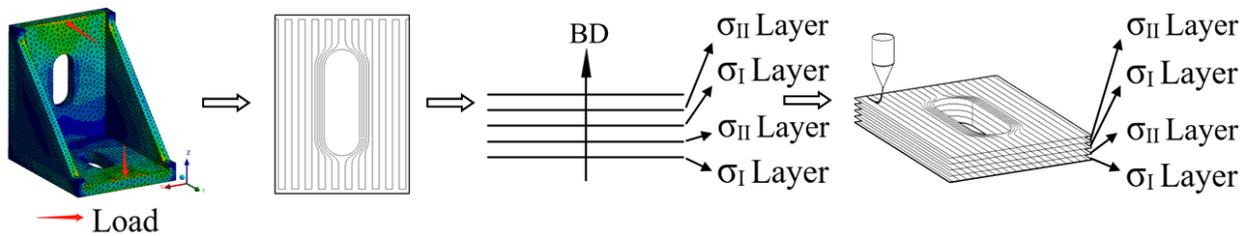


Fig.5 Toolpath generation based on PSL

Experimental Platform

In order to implement the multi-area and multi-direction building (MMB) strategy which is based on the proposed theory and methodology in this paper, a 6-axis robot arm (EPSON S5-A901S) integrated with FDM extrusion system is constructed to overcome the disadvantage of the traditional 3-axis MEX process (actually with 2.5D motion) with only one single BD (theoretically the BD can be 0-180 degree compared to traditional 90 degree).

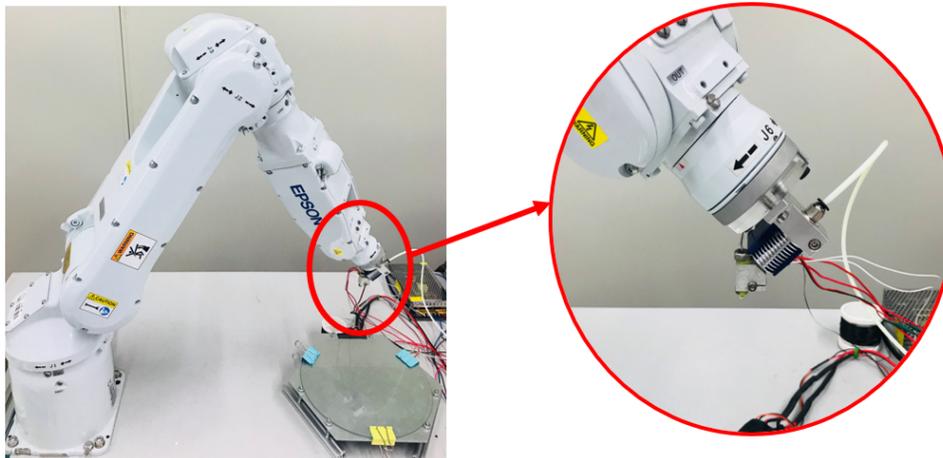


Fig.6 A 6-DOF robot arm integrated with FDM extrusion system

G-code translation

Traditionally, the G-code, which is the control code for the motion of the traditional MEX system and is obtained in slicing process using traditional slicing software, contains key parameters of the MEX process such as temperature, extrusion speed, slice thickness, printing path and printing speed. For this 6-DOF MEX system, the motion of the extruder (i.e. slice thickness, printing path and printing speed) is controlled by the robot arm which is programmed by SPEL+ code (for EPSON RC170/180 controller). To realize the synchronous control on extruder and robot arm, currently, a “3D print G-code to EPSON SPEL+ translation software” is developed using Java which can translate the G-code to SPEL+, to integrate the control of the extruder into the control of robot arm by Arduino. The framework of this translation process is shown in Fig.7.

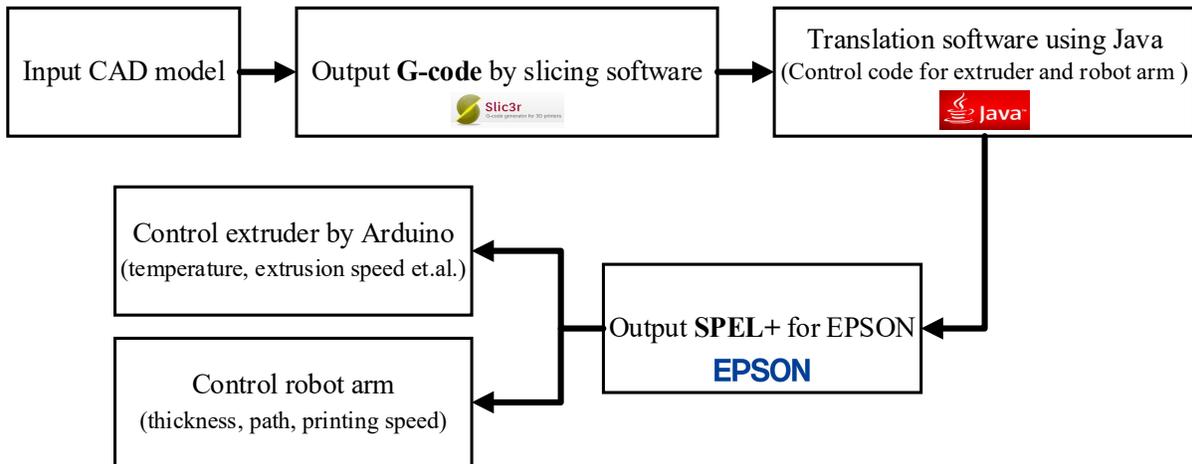


Fig.7 Translation from traditional printed G-code to robot programming language

Preliminary Results and Discussion

A test part with material of PLA followed the shape of bracket connector was printed as a case study using the above discussed methodology. In this case, the part is divided into three building areas and is built in three different BD. The building sequence is ①→②→③ (see Fig.8(II)). The connectivity between different building areas and the quality of the surfaces which are perpendicular to the BD are good. The feasibility of this methodology is preliminarily verified. And theoretically, the mechanical performance of the part will be improved while the building direction for each building area being in alignment with the corresponding direction of force flow. For further verification, a standard part will be constructed using this method, and its mechanical performance will be tested comparing with the part made by traditional process.

As for the surface quality, the surfaces which are perpendicular to the BD are much better than the side surfaces. There are some defects we found in this case, which should be improved in future work. As shown in Fig.8(III), there is a crack between area ① and ③ on the interface. Because the extrusion head can't reach the corner space owing to the collision between the head and area ①. To solve this problem, the building sequence and dividing of building areas including BD should be optimized which have significant influence on the quality of printed part, for example, following the sequence of ③→②→① (area ③ in the bottom). In addition, the collision can also be avoided by improving the structure of extrusion head (e.g. with a slender shape).

Moreover, there are some material squeezed out of the body, especially in the small-size corner of area ②, which cause deterioration of the surface quality. There are many factors that will cause this defect, for example unsuitable toolpath (e.g. the tool path for building the inner layers are often different from that of the outer layers) and low accuracy of moving control of this MEX system, which should be improved in future work.

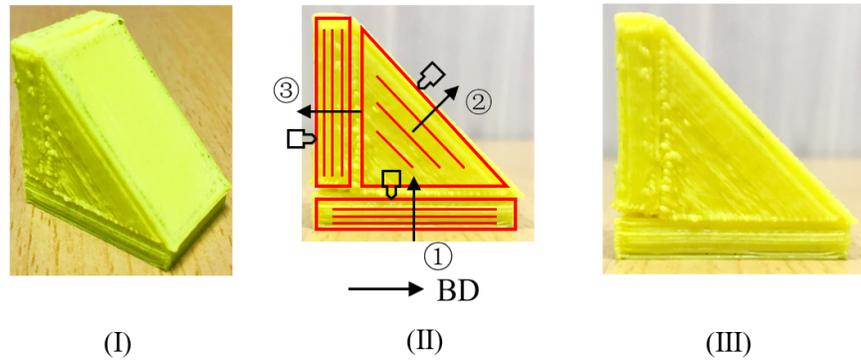


Fig.8 The printed sample using MMB strategy

The proposed methodology is elaborated with the example of bracket connector part which has planar geometric features. For future research, the strategy of curved layers additive manufacturing (CLAM) (see Fig.9) can be studied to fulfill the construction of part containing curved surfaces, including the strategy for slicing and generating toolpath, which can improve the finish of the curved surfaces, and the mechanical performance considering the continuous transmission of force in geometry parts.

Additionally, in this paper, the theory and methodology of high-performance additive manufacturing is based on the consideration of stress fields. Further thinking, the physical performance of additively manufactured parts can be improved and customized considering some other fields, such as temperature fields, magnetic fields and electric fields, or the coupling of multi-physical fields. This is what we call the field-oriented additive manufacturing (FOAM) (see Fig.10). We think there will be a great research value and application prospect for FOAM, which will advance the customization of parts from “geometry” to “function” and then to “performance”, for example, the part with same geometry may be printed with different internal structures due to its customized physical performances.

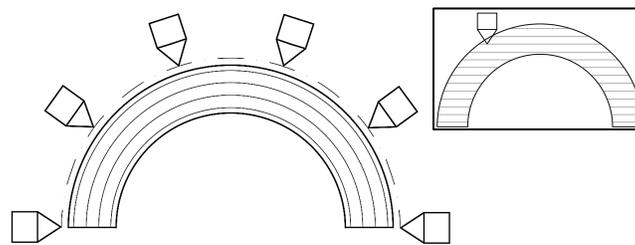


Fig.9 Curved layers additive manufacturing

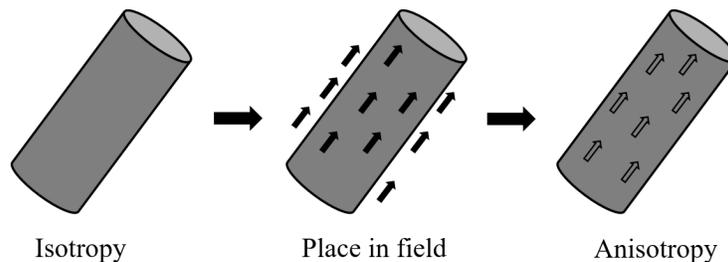


Fig.10 Filed oriented additive manufacturing

Conclusion

In this work, a theory and methodology is proposed to minimize the adverse influence of anisotropy on mechanical performance of the MEX part by designing and controlling anisotropy under the guidance of force-flow. For the anisotropy between different layers, corresponding building areas and BD are planned considering the weak links between different layers; for the anisotropy within layers, corresponding toolpath of each building area is generated according to the PSL considering the weak links between different filaments. A 6-axis robot arm integrated with extrusion system is constructed to implement the MMB, and its feasibility has been proved by the preliminary tests.

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